Life cycle assessment of scalable R2R-manufactured flexible perovskite solar cells

Mae Xerzel Ouano[1], Erica Magliano[2], İlker Doğan[3], Sebastien Lizin[1]

[1]Hasselt University, Belgium; [2]CNR-ISM, Italy; [3]TNO, The Netherlands

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1 Introduction

The promise of flexible perovskite cells

Opportunities for new applications, such as vehicle-integrated and building-integrated PVs

Potential for high throughput production through roll-to-roll (R2R) manufacturing

TNO develops world's first perovskite solar roof tile

Solar applications **2 April 2026**

TNO has taken an important step in the development of solar energy. By better integrating solar energy into buildings, more space is created for sustainable electricity generation without additional strain on landscape or infrastructure.

Figure 1. First demonstration of integrating flexible perovskite cells on a roof tile (TNO, 2026)

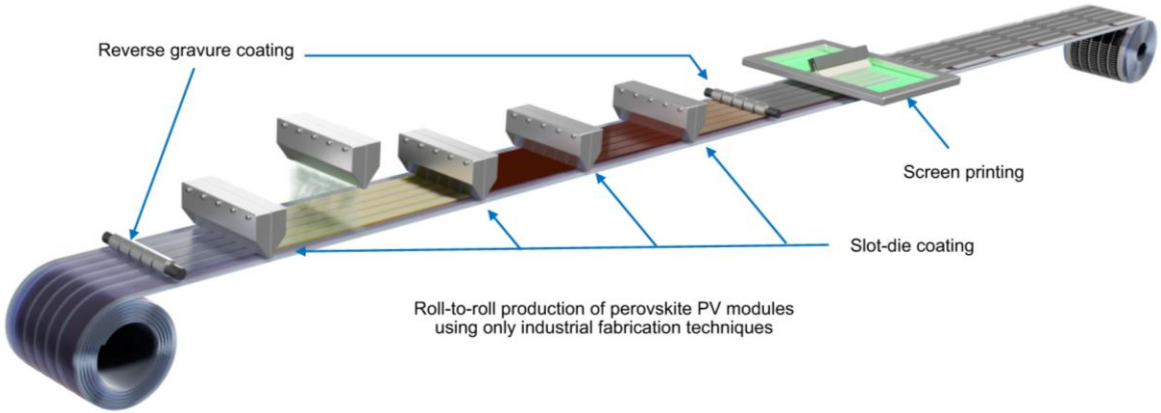
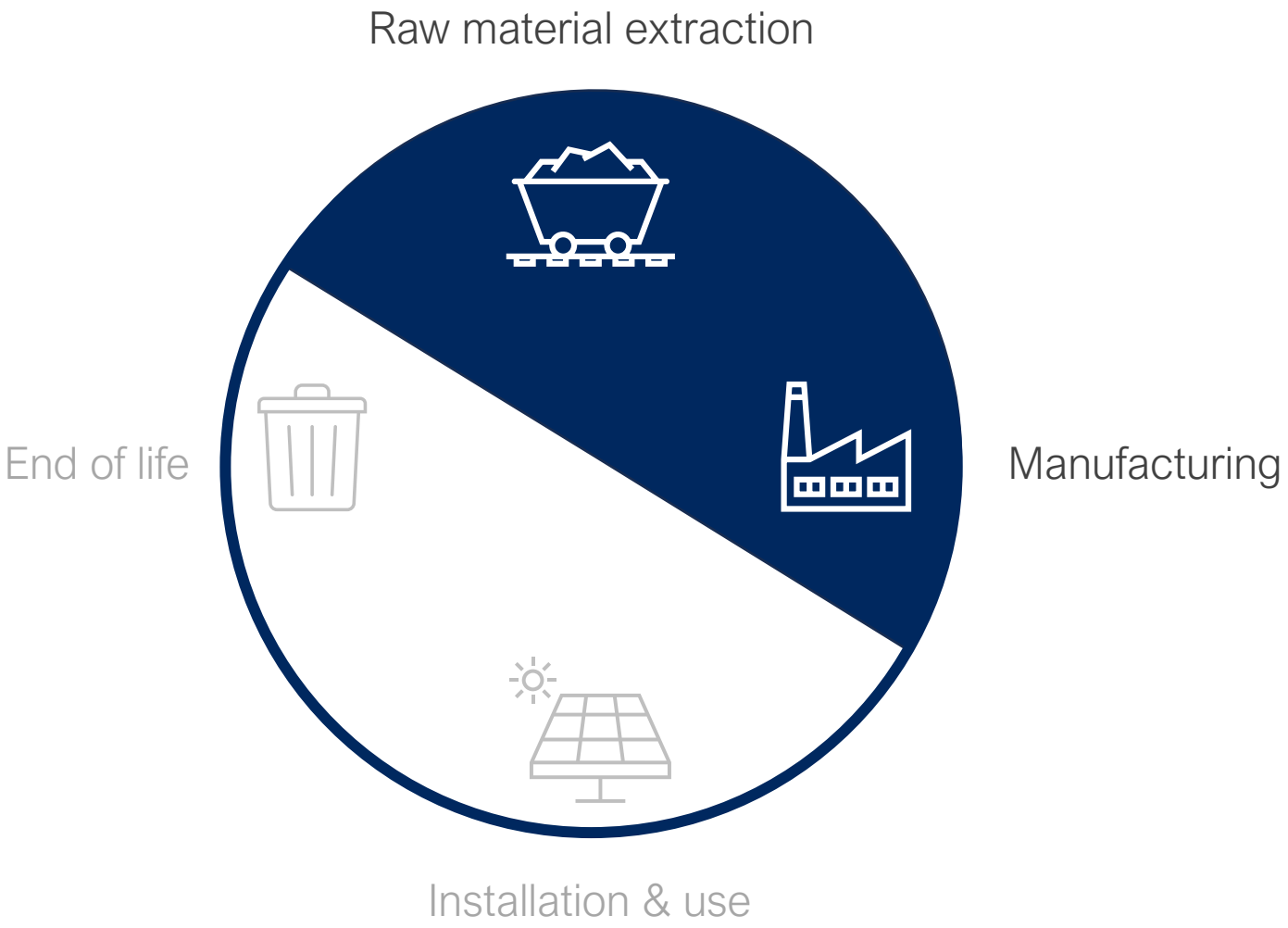


Figure 2. Schematic illustration of R2R production of modules using slot-die (SD) coating, reverse gravure (RG) coating and screen printing (Weerasinghe *et al*., 2024)

In contrast, silicon-based modules are manufactured through **sheet-to-sheet (S2S)** processing

Ecodesign of flexible perovskite cells

To make more sustainable photovoltaic (PV) modules



For emerging PVs, ecodesign strategies are essential before unsustainable designs reach commercial scale and are locked in

Focus on material substitution and process energy efficiency

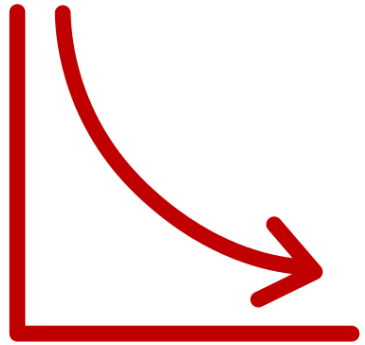
Ecodesign of flexible perovskite cells

Are they more sustainable than rigid modules (e.g., silicon-based)?

Solution-processability of perovskites

Lightweight flexible substrates

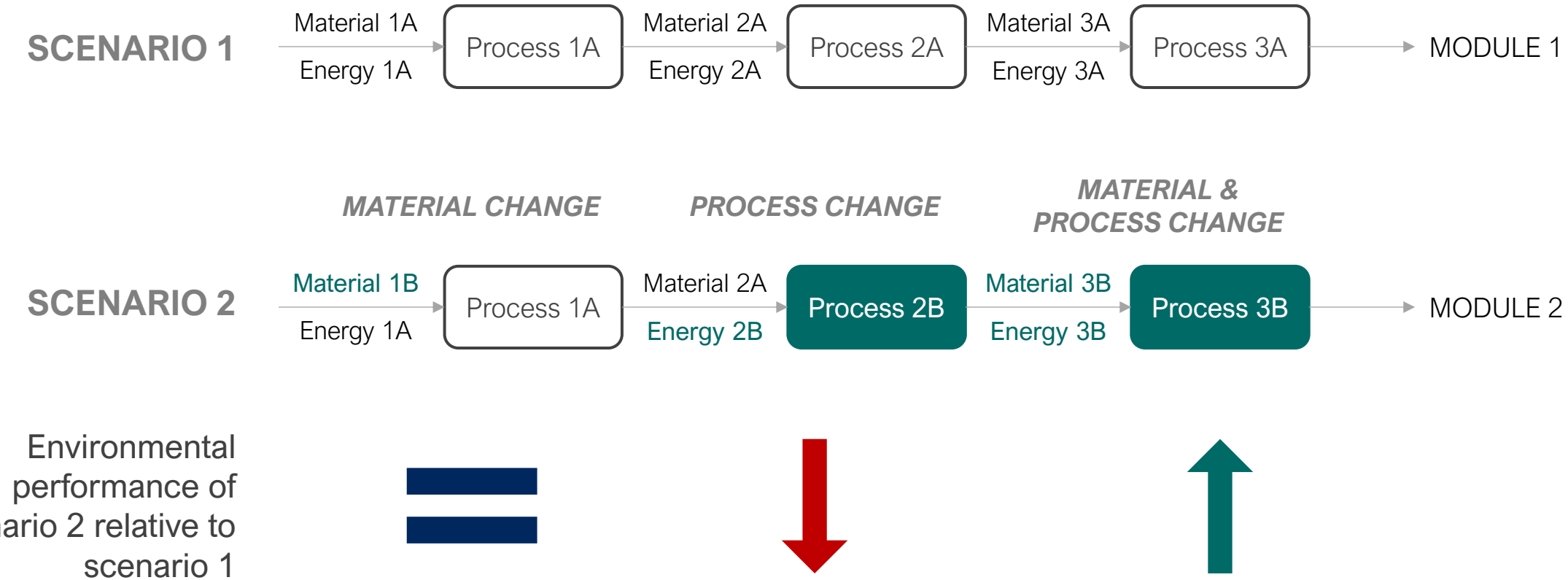
Lower material and energy consumption of module manufacturing



Lower long-term stability

Ecodesign of flexible perovskite cells

How can we make flexible perovskite manufacturing less environmentally impactful?

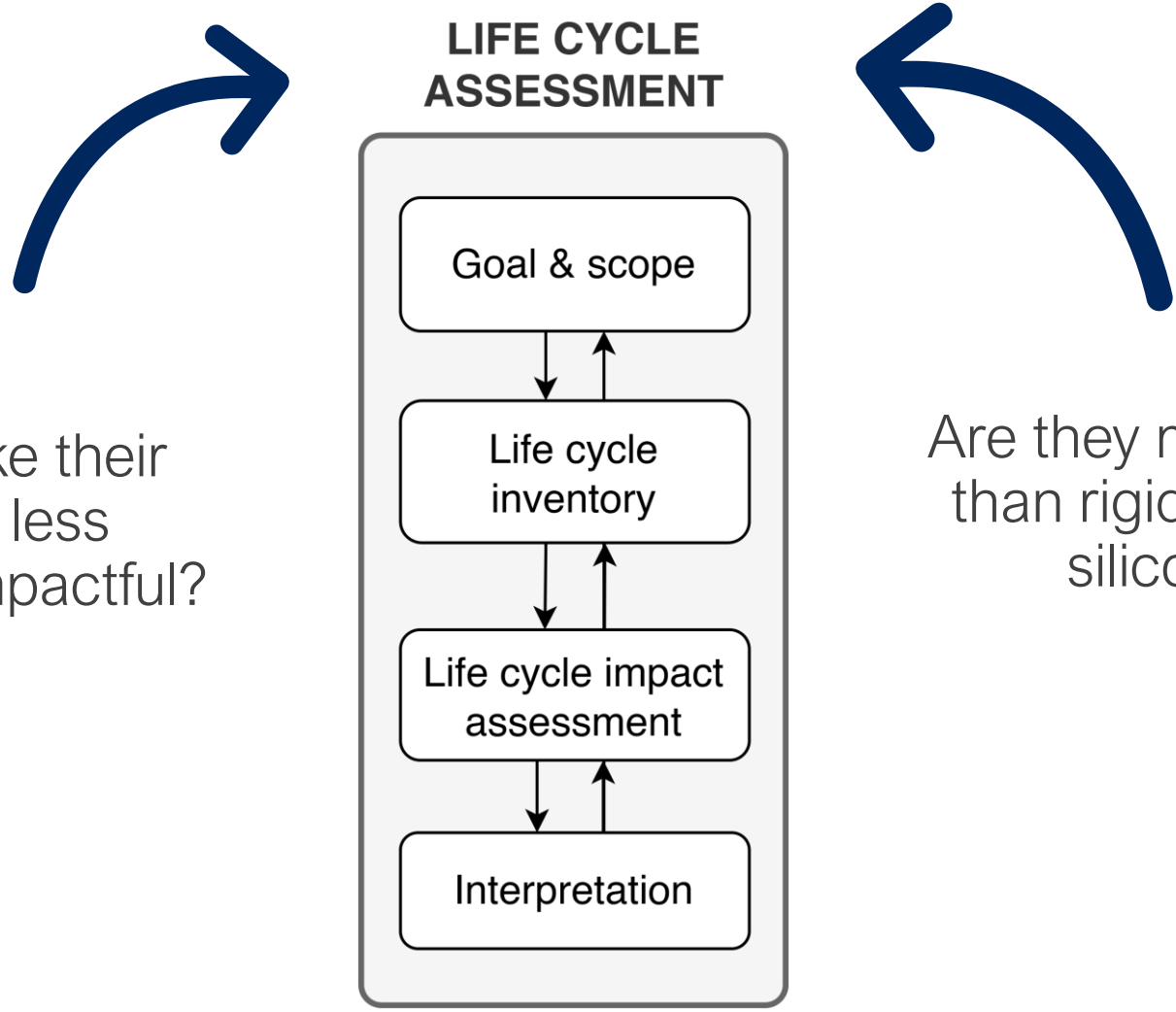


Choosing better materials and processing methods for the commercialization of flexible perovskite manufacturing

Ecodesign of flexible perovskite cells

LCA as an ecodesign tool

How can we make their manufacturing less environmentally impactful?



Are they more sustainable than rigid modules (e.g., silicon-based)?

Gaps

Current LCAs on flexible perovskite modules (f-PSMs)

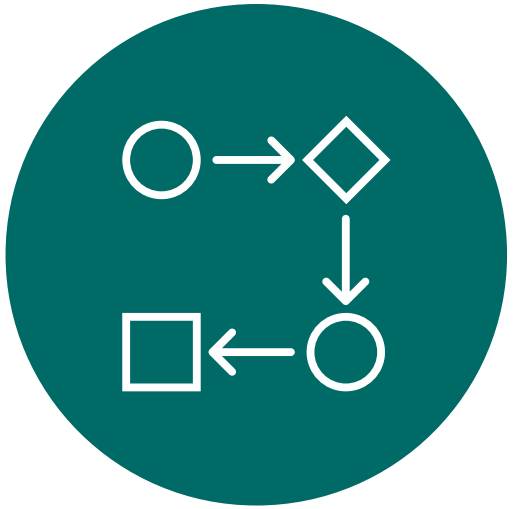
Considers non-scalable processes

Deposition methods, such as spin coating, are still considered in the analysis

Studies are based on lab-scale data

Lab-scale data are still used as inputs, which overestimate the environmental impacts if used for industrial scale scenarios

Aims of the study



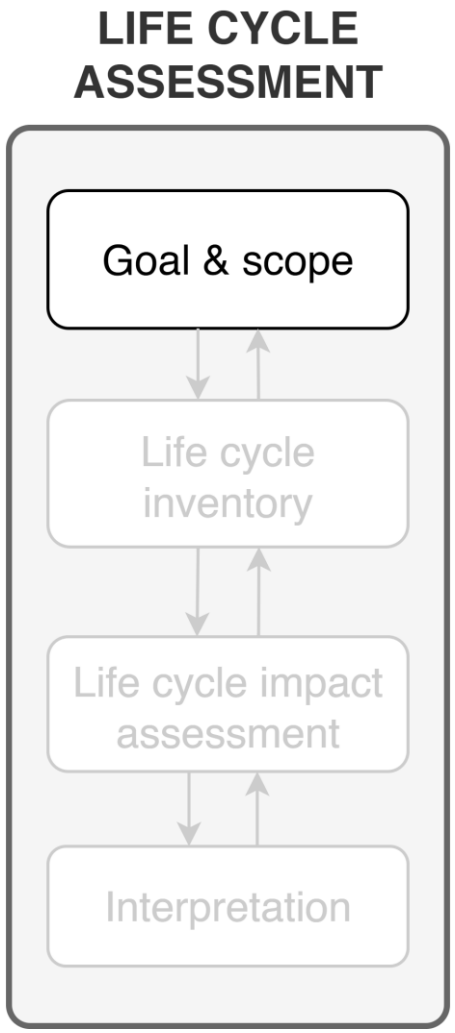
Identify process and material hotspots in a scalable flexible perovskite module manufacturing line

Compare the environmental impact results to those of rigid c-Si and perovskite modules

2 Method

Goal & scope

Scalable R2R-compatible manufacturing of flexible perovskite solar modules (f-PSMs)



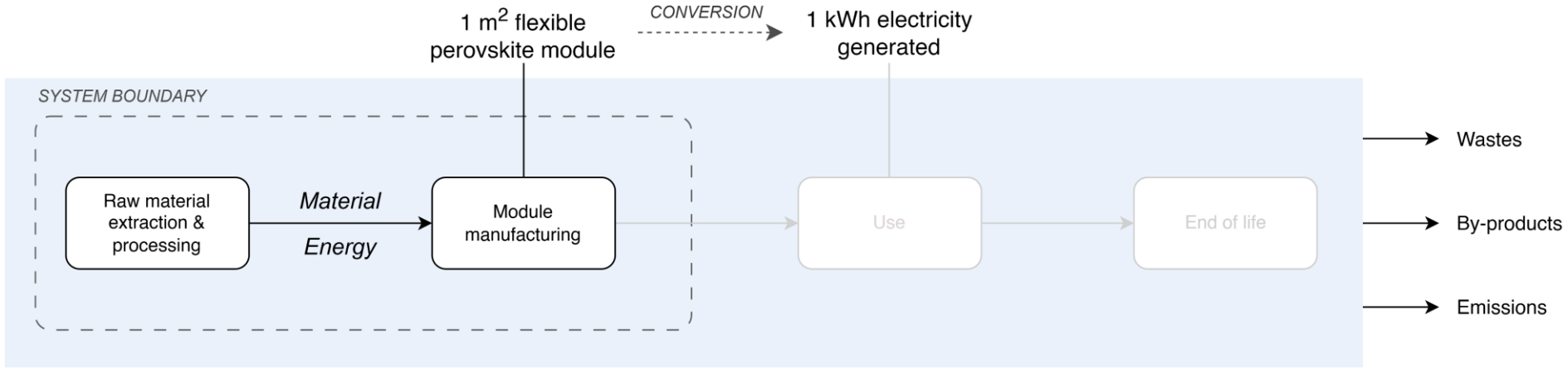


Figure 3. System boundary of the PV system considered in this study

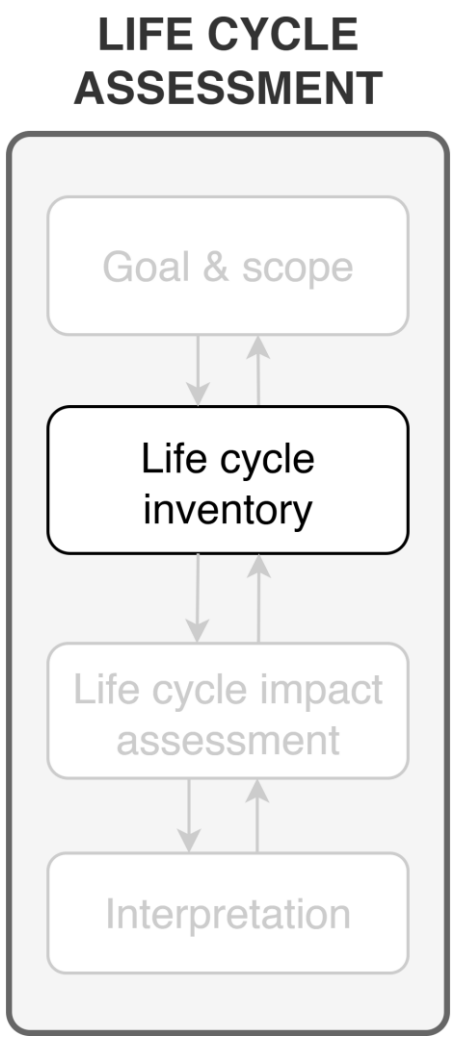
GOALS Evaluate the environmental impacts of manufacturing 1 m^2 of flexible single-junction perovskite modules with different (p-i-n) cell stack architectures

Compare the environmental impacts of generating 1 kWh of electricity by flexible perovskite modules with those of rigid c-Si and perovskite modules

LOCATION Europe

Life cycle inventory

Scalable R2R-compatible manufacturing of flexible perovskite solar modules (f-PSMs)



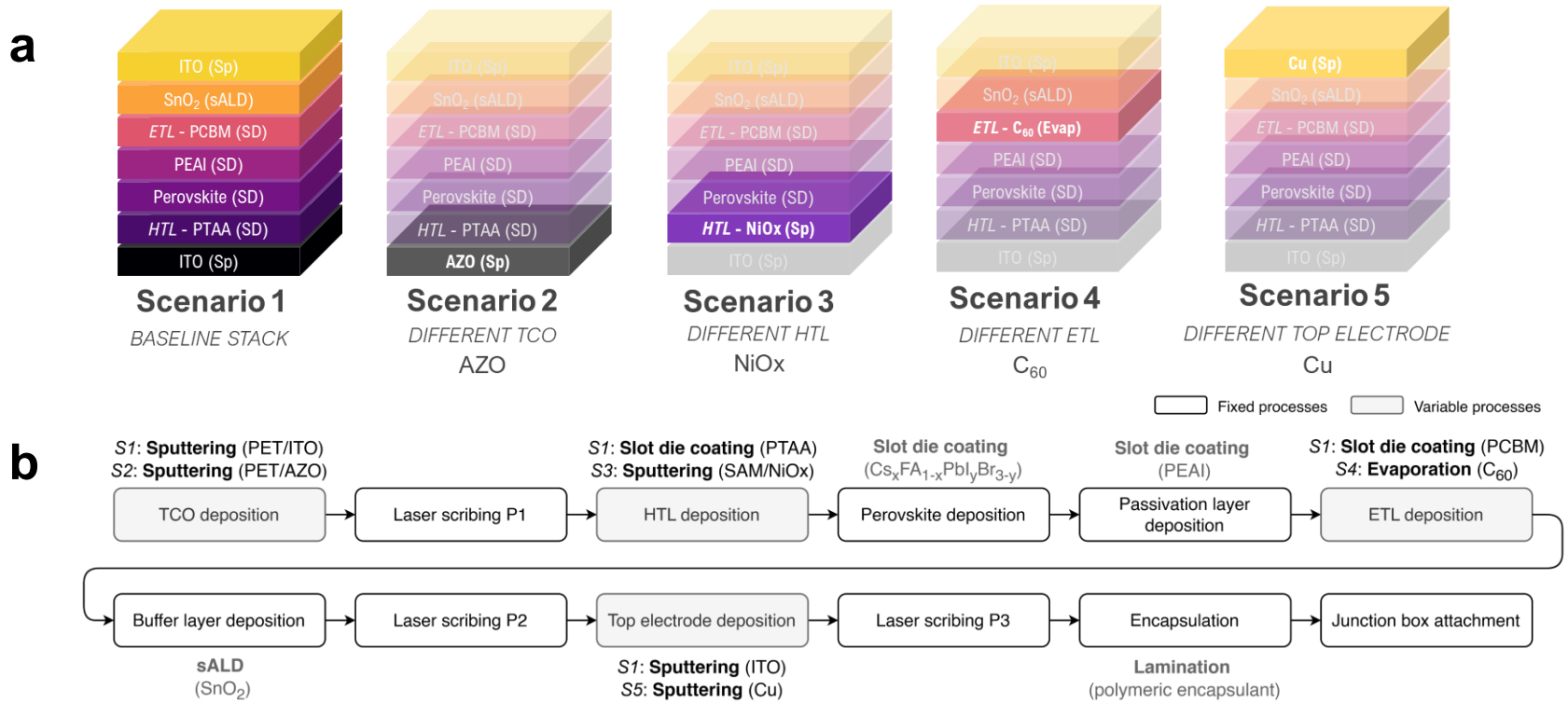


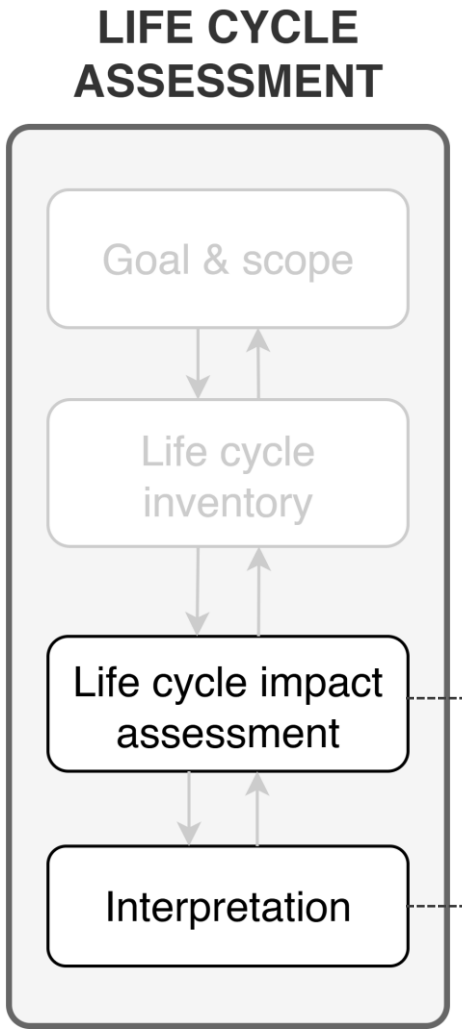
Figure 4. (a) Stack architectures for each scenario and (b) process steps in f-PSM manufacturing considered in the analysis

FOREGROUND DATA Perovskite: primary (pilot scale) data from project partners and data from literature
c-Si: inventory from IEA PVPS 12 report (Frischknecht et al., 2020)

BACKGROUND DATA ecoinvent v3.11

Life cycle impact assessment and Interpretation

Scalable R2R-compatible manufacturing of flexible perovskite solar modules (f-PSMs)



IMPACT CATEGORIES	17 total Environmental Footprint 3.1 (16) and Cumulative Energy Demand (1)
TOOL	Brightway 2.5

HOTSPOT ANALYSIS	Identify the most impactful materials and processes
SCENARIO ANALYSIS	Determine the difference per material/process change
SENSITIVITY ANALYSIS	Evaluate the effect of changing parameters on impacts

3 Results & discussion

Process hotspots

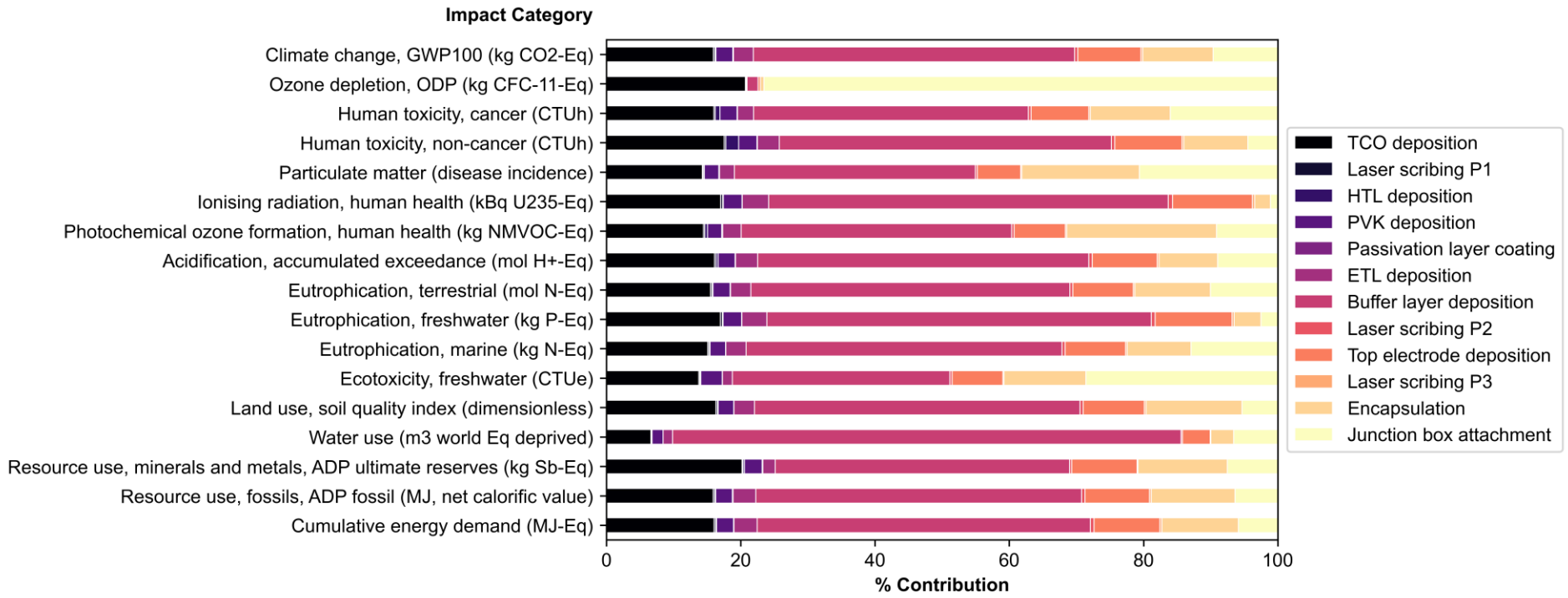


Figure 5. Percent contribution per layer for all impact categories for f-PSM scenario 1

- Global warming potential (GWP) results of all scenarios are in the range of 27-28 kg CO_2-Eq/m^2
- Buffer layer deposition, which uses spatial atmospheric layer deposition (sALD), has the highest contribution in almost all categories
- Process hotspots of all scenarios are similar

Material hotspots and scenario differences

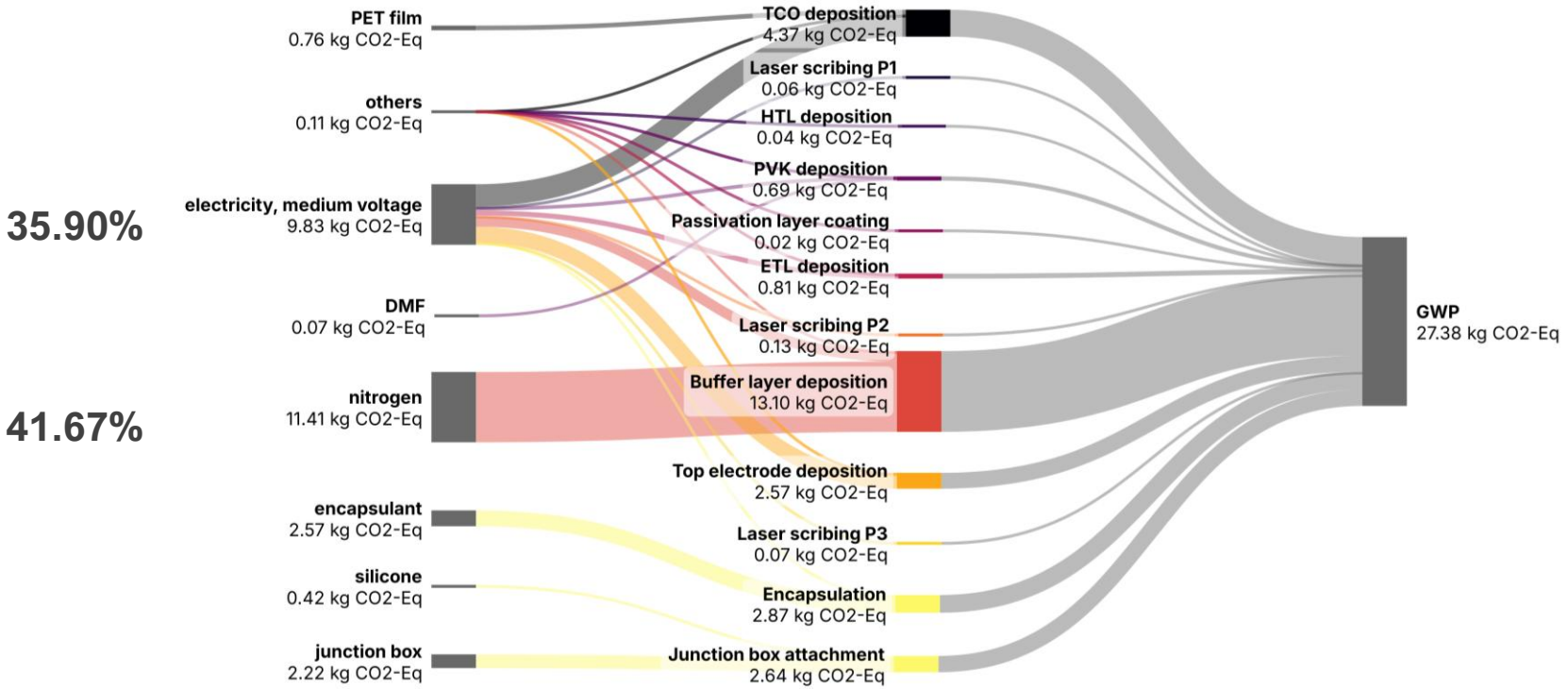


Figure 6. Global warming potential (GWP) process and material contributions per m^2 for f-PSM scenario 1

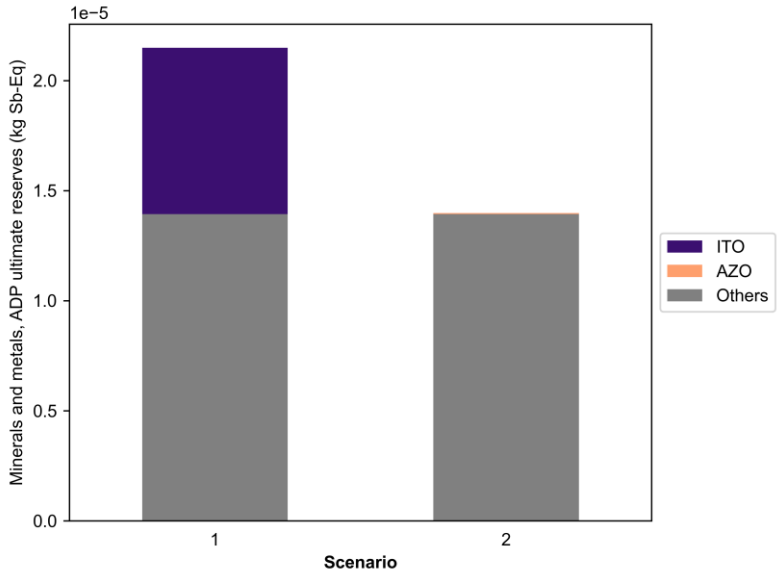
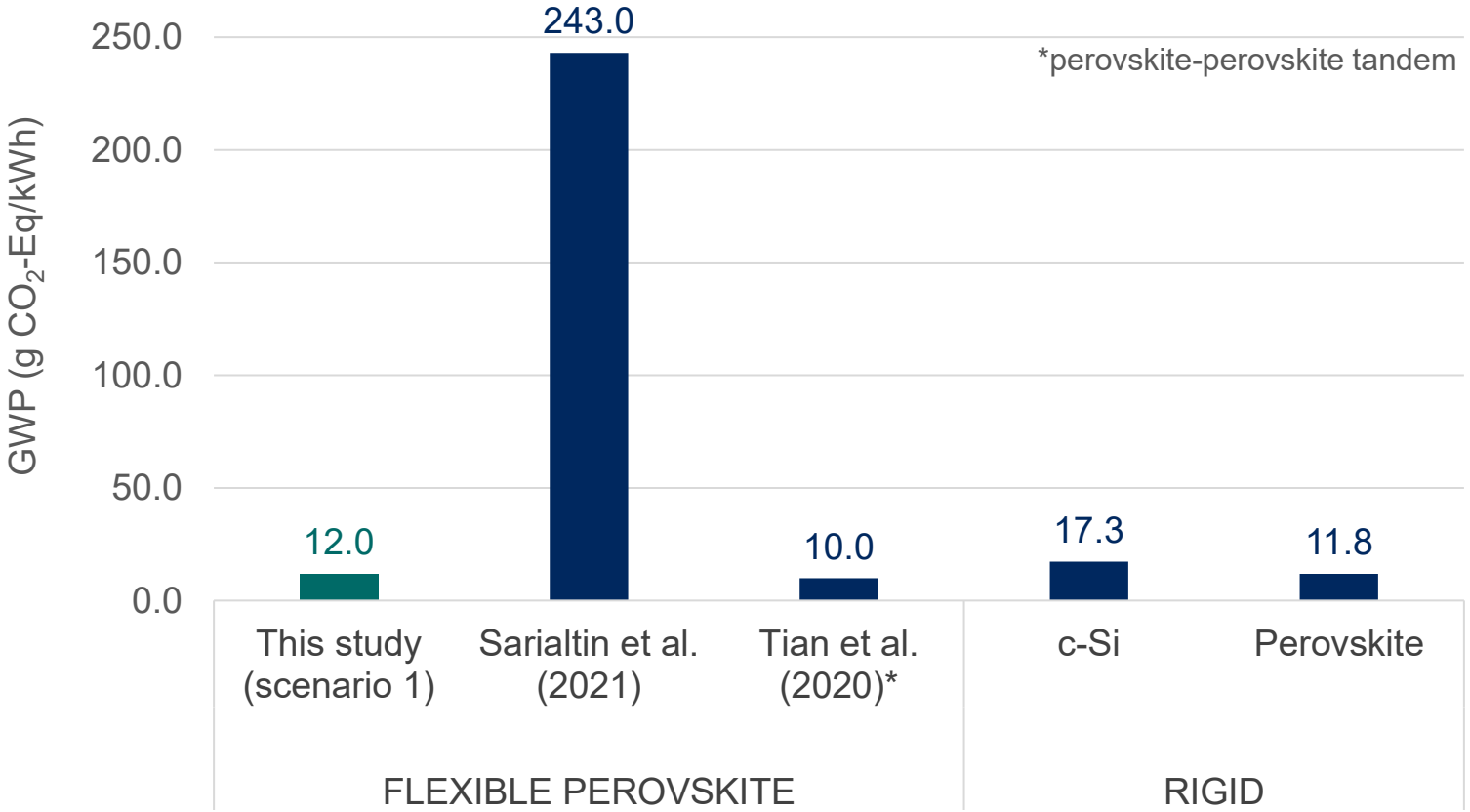


Figure 7. Resource use results per m^2 for TCO deposition

- High nitrogen consumption in the sALD process is the main material hotspot, followed by electricity consumption
- Although there are minimal differences in the impact results for each scenario (a maximum of ±5% difference relative to scenario 1), ITO substitution with AZO shows the highest difference in the resource use impact category (-7%)

Comparison of GWP results



	This study (scenario 1)	Sarialtin et al. (2021)	Tian et al. (2020)*	c-Si	Perovskite
PCE (%)	15.0	14.0	23.1	20.9	21.1
Lifetime (years)	15	5	15	30	15

Figure 8. GWP results for f-PSM compared to rigid modules

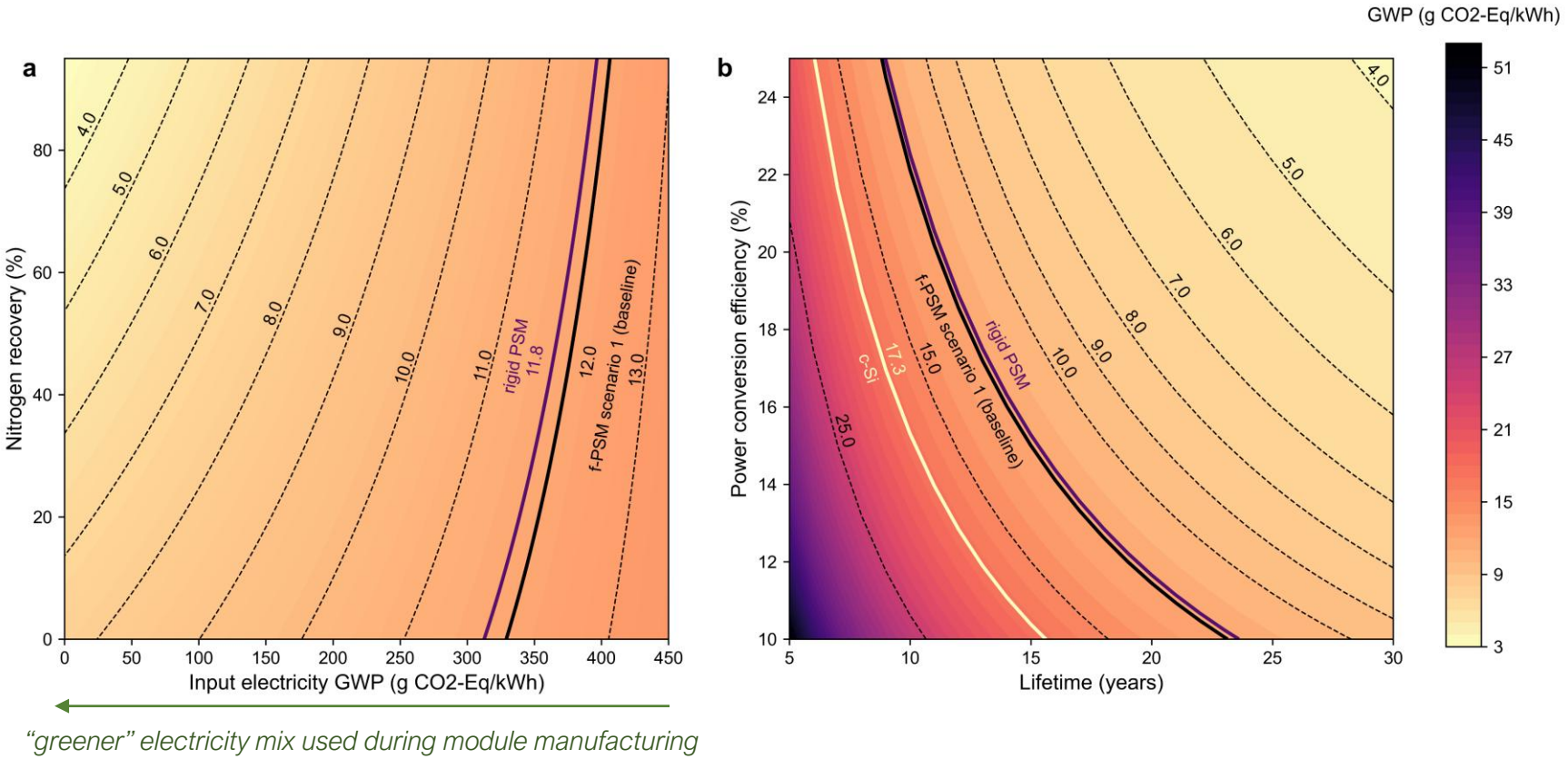
On a per m^2 basis, the GWP of f-PSM scenario 1 is:

- ~27% lower than a rigid perovskite module (38 kg CO_2-Eq/m²)
- ~73% lower than a c-Si module (106 kg CO_2-Eq/m²)

Compared to literature:

- Sarialtin et al. (2021) uses spin coating in depositing multiple layers
- Tian et al. (2020) evaluates a flexible perovskite-perovskite tandem module, while this study considers a flexible single-junction module

Sensitivity analysis



"greener" electricity mix used during module manufacturing

Figure 9. Effect of changing (a) production parameters (nitrogen recovery in sALD and electricity GWP impact factor) and (b) performance parameters (PCE and lifetime) on the GWP of f-PSM scenario 1

Module lifetime is the most impactful parameter in reducing GWP

For production parameters to reduce GWP by **1 g CO_2-Eq./kWh** of f-PSM

- Nitrogen recovery to **reach 55%**
- Electricity mix GWP impact factor to **reduce by 24%** (EU average market group GWP: 329 g CO_2-Eq./kWh)

4 Conclusions & Future Work

Conclusions

- Flexible perovskite modules have GWP results (in per kWh) that are lower than c-Si modules and comparable to rigid perovskite modules
- The integration of pilot-scale input data from scalable deposition methods reduces GWP impacts
- Consider possible material/energy trade-offs for scalable deposition methods

Ecodesign recommendations based on results

- Consider process gas recovery in manufacturing, especially for deposition processes that use large quantities of gases
- Seek out alternatives to ITO as an electrode to address indium scarcity
- Choose a specific location with a green electricity mix and/or that uses renewable energy sources
- Focus efforts on improving the stability, as it is highly impactful in reducing flexible perovskite environmental impacts

Considerations for future work

- Evaluate an alternative deposition method for buffer layer deposition step
- Conduct a prospective LCA on an industrial-scale manufacturing line by:
  - upscaling the direct material and energy inputs and developments in the background over time
  - integrating more stakeholder input in the evolution of future manufacturing scenarios

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Mae Xerzel Ouano

maexerzel.ouano@uhasselt.be

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